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SUPERCONDUCTING WIRE TEST AT FERMILAB*

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ABSTRACT

An extensive study on superconducting wires is being conducted at Fermilab for the Energy Doubler Project. The major tests are short-sample test, and AC loss test, including hysteresis loss test. In this paper, we report mainly the method and some measurement data of AC loss test.

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I. INTRODUCTION

We have been testing superconducting wire for the Energy Doubler Project at Fermilab. The important parameters of superconducting wires, in which we are most interested, are short-sample test data for designing maximum field, and AC loss data for cryogenic requirements.

The maximum current for the Energy Doubler model magnets is in the range of 3000 A to 5000 A, depending on the type of wires. To be close to a practical case, we are doing short-sample tests and AC loss tests with this high-transport current. This involves power supplies with 5000 A current capacity and heavy current carrying conductors. These make the measurement a little awkward to handle compared with a measurement involving a single-strand wire. But, by testing with full current capacity, we can see all of the effects, which might be missed otherwise.

II. SUPERCONDUCTING WIRES

The final wire for the Energy Doubler has not been determined yet. Two years ago, we were thinking of building an accelerator with a cycle of 1,000 sec, corresponding to 0.1 kG/sec rate. We were investigating both solid and multistrand cabled NbTi superconductors with dimensions of 75 × 150 mils and 50 × 150 mils. They were two component conductors with copper as the matrix.

Now we have switched completely to Rutherford type cabled superconductors because of the recent improvement in the commercial manufacturing capabilities. The dimensional parameters are still undecided. Presently we are testing also 13-strand, 17-strand, and 23-strand cables with dimensions of 75 × 250 mils, 50 × 250 mils, and 50 × 300 mils respectively. The last two of them have superconducting filament 7.9-μm in diameter, and have 39,100 and 52,900 filaments. This small filament size brought down the AC loss and made it possible to go to a higher sweep rate. We are contemplating building an accelerator with a ramp rate of a few kilogauss per second or so.

III. SHORT-SAMPLE TEST

The critical current of superconducting wires vs field are measured using a 75-kG solenoid magnet with 3-in. bore diameter and 10-in. length. The circuit diagram is shown in Fig. 1. The method of this measurement is reported in detail elsewhere.[1] The detailed data are reported in other reports.[2] Typical short-sample data are shown in Fig. 2. In these reports, short-sample test data on regular lead-tin solder, and some crimped joints of superconducting wires are also reported.

IV. AC LOSS

AC loss of a wire consists of hysteresis loss and eddy current loss. Hysteresis loss is a constant per cycle and a major part of loss for slow pulsing. It was measured with a slow rising solenoid magnet. AC loss, which is a total loss, was measured with a fast-rising solenoid. Eddy current loss includes filament coupling loss in a strand, self-field loss due to transport current, and the loss due to eddy currents between strands. These losses usually increase with faster ramp speed and depend on the orientation of the wire to the direction of magnetic field.

1. Hysteresis Loss Test

The magnetization of superconducting wires for DC operation is measured using the same 75-kG solenoid which is used for short-sample test. The schematic drawing is shown in Fig. 3. A similar setup has been developed and reported.[3] There are two identical search coils inside the solenoid. The dimensions of these coils are as follows: the inner diameter 0.83 in., outer diameter 0.93 in., the respective turn numbers 620, and the effective area 3.92 cm^2. These twin coils are placed 5.0 cm apart at the center of the solenoid.

Samples are cut into 2.0-in. length and packed into a capsule with inside diameter of 0.63 in. The capsule is moved in and out of one of the twin search coils from the top using a long G-10 tube.

The leads of the twin coils are brought outside, connected to an individual 10-turn 5-kΩ potentiometer, and bucked against each other. The setting of the potentiometer is adjusted to have a zero signal when the magnet is excited without a sample. The difference signal, with a sample placed in one of search coil, is integrated with an integrator with an input resistance of 0.1-MΩ and a capacitor of 0.1 μF. The output of the integrator is connected to the Y axis of the X-Y recorder. The signal ranged in magnitude from 0.1 V to 0.4 V depending on the sample. The current of the solenoid is measured with a 50 mV/500-A shunt and its signal is connected to the X axis of the recorder.

As the superconducting accelerator is going to be excited from an injection field (9 kG) up to 45 kG, the hysteresis losses were measured correspondingly from 9 kG up to 45 kG. The samples were also measured from 0 kG up to 45 kG. The typical magnetization curves are shown in Fig. 4, which is a composite of 9-, 18-, 27-, 36-, and 45-kG operations. There are some humps in the curves because the power supply was not moving smoothly. A typical curve was measured in 2 minutes, corresponding a sweep speed of 0.5 kG/sec. Measurement below 9 kG was done with a smaller power supply which is smoother in operation.

The area inside the loop of X-Y diagram represents the hysteresis loss W_h and can be calculated as follows:[4]

$$W_h = \frac{1}{4\pi} \oint HdB.$$

Where H is given in Oersted, B in Gauss, and W_h in erg/cm^3. The calculated curves are shown in Fig. 5 for both types of operation, with vertical scales in Joules per cubic centimeter of superconductor and in Joules per meter of wire. The high-field curves of many samples can be fit with a linear line and below their penetration field values they can be approximated with cubic lines. When a sample was measured at low field after being excited to higher field, it showed a quadratic curve at low field. In these measurements, the wire samples were placed along the field directions. Other orientations are being studied.

The hysteresis loss of some niobium films for the superconducting power transmission group was measured using the same equipment.

2. AC Loss Test

The AC loss of the superconducting wire including hysteresis loss is measured by the watt-meter method.[5] The voltage across a self-excited solenoid coil is multiplied by the current value, giving an instantaneous wattage. Then, this value is integrated over a cycle. The present setup is an on-line system, and data can be taken in a very short time.

The AC loss test setup is shown in Fig. 6. The terminal voltage of the sample coil is taken out and balanced with a signal voltage taken from a bucking coil placed inside the sample coil. In this way most of the inductive voltage of the sample coil is cancelled leaving only loss voltage.

The sample coil is wound with an MCA 13-strand wire. It has dimensions of the inner diameter of 2.0 in., the outer diameter of 2.7 in., and the height of 2-7/8 in. It has 4 layers of 11 turns/layer, and the total length of wire is 7.8 meters. The sample coil is excited with a Transrex 500-5 power supply, using chokes and resistors to suppress the noise coming from the power supply.

The balanced signal is amplified by a DANA DVM 5333 by a factor of 100. The current through the sample coil is read by a shunt of 50 mV/5000 A. Each signal is input to an individual differential plug-in amplifier 7A22 of the Tektronix Digital Processing Oscilloscope (DPO), digitized to 512 points during the sweep across the face of the scope, and stored in the 4-k core memory of the DPO. The data are then sent to the PDP11/10 and processed. The voltage and current are multiplied, and the instantaneous wattage is integrated to get a total energy loss W_{ac} over a cycle.

$$W_{ac} = \int V\, I\, dt$$

The computer printouts of waveforms of current, balanced voltage, multiplication of these two, and its integration, are given in Figs. 7, 8, 9, and 10. The total energy loss W_{ac} is also printed out.

The AC loss was measured with different maximum amplitudes, starting from zero field but with the same ramp speed of 1.1 kG/sec. The data are shown in Fig. 11 for the maximum field range from 2 kG to 25 kG. Around 3.5 kG, there is a definite bend in the curve, showing approximately linear behavior above it, and quadratic below it. The vertical scale is given in Joules/cycle.

The ramp rate dependence was measured changing the speed from 0.4 to 5 kG/sec, keeping the maximum field at 7.6 kG. The data are shown in Fig. 12. The eddy current effect is about 50% of the DC hysteresis loss at 5 kG/sec. In this measurement the wide surface of the wire was parallel to the field. Different orientation of wire are also being studied.

ACKNOWLEDGMENT

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REFERENCES

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[2] Fermilab Internal Reports TM-538, Nov. 23, 1974; TM-567, March 24, 1975; TM-587, June 26, 1975.

[3] W. A. Fietz, Rev. Sci. Instr. 36, 1621 (1965).

[4] C. P. Bean, Rev. Mod. Phys. 47, 31 (1964).

[5] A similar device has been developed by W. S. Gilbert, LBL, Berkeley, California, private communication.

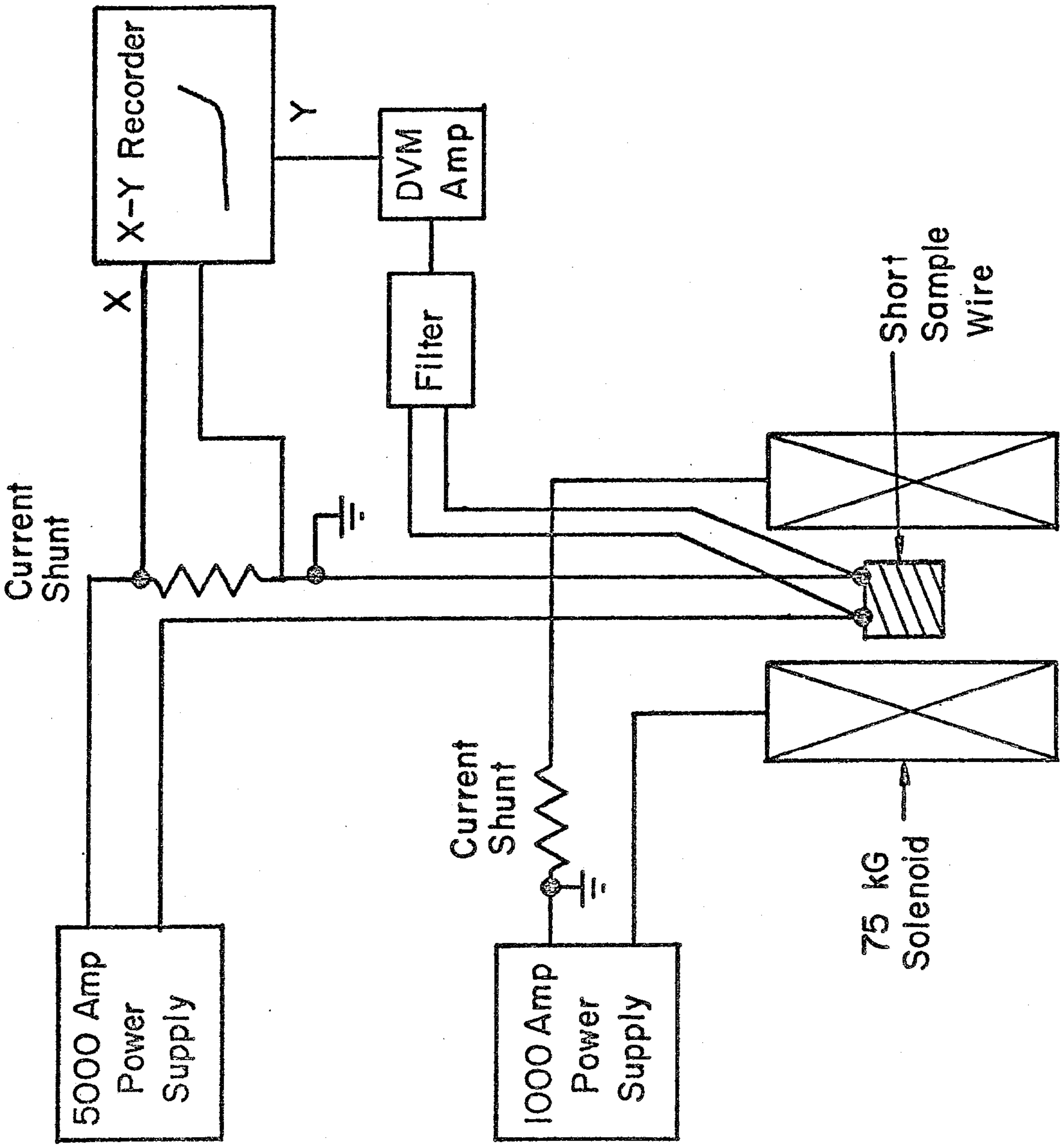

Fig.1 Block Diagram of Short Sample Test

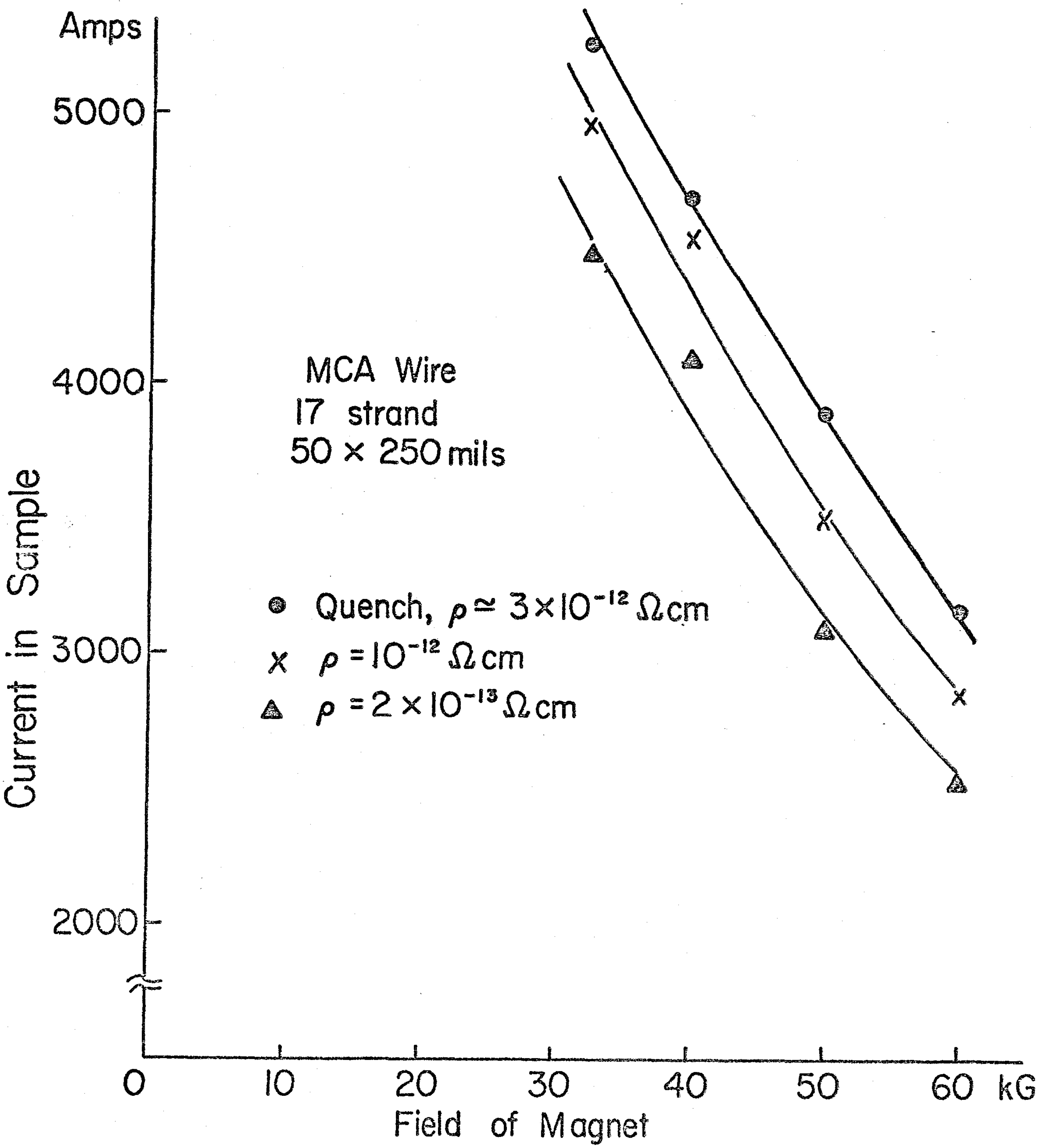

Fig. 2 Short Sample Data of MCA 17 Strand Wire

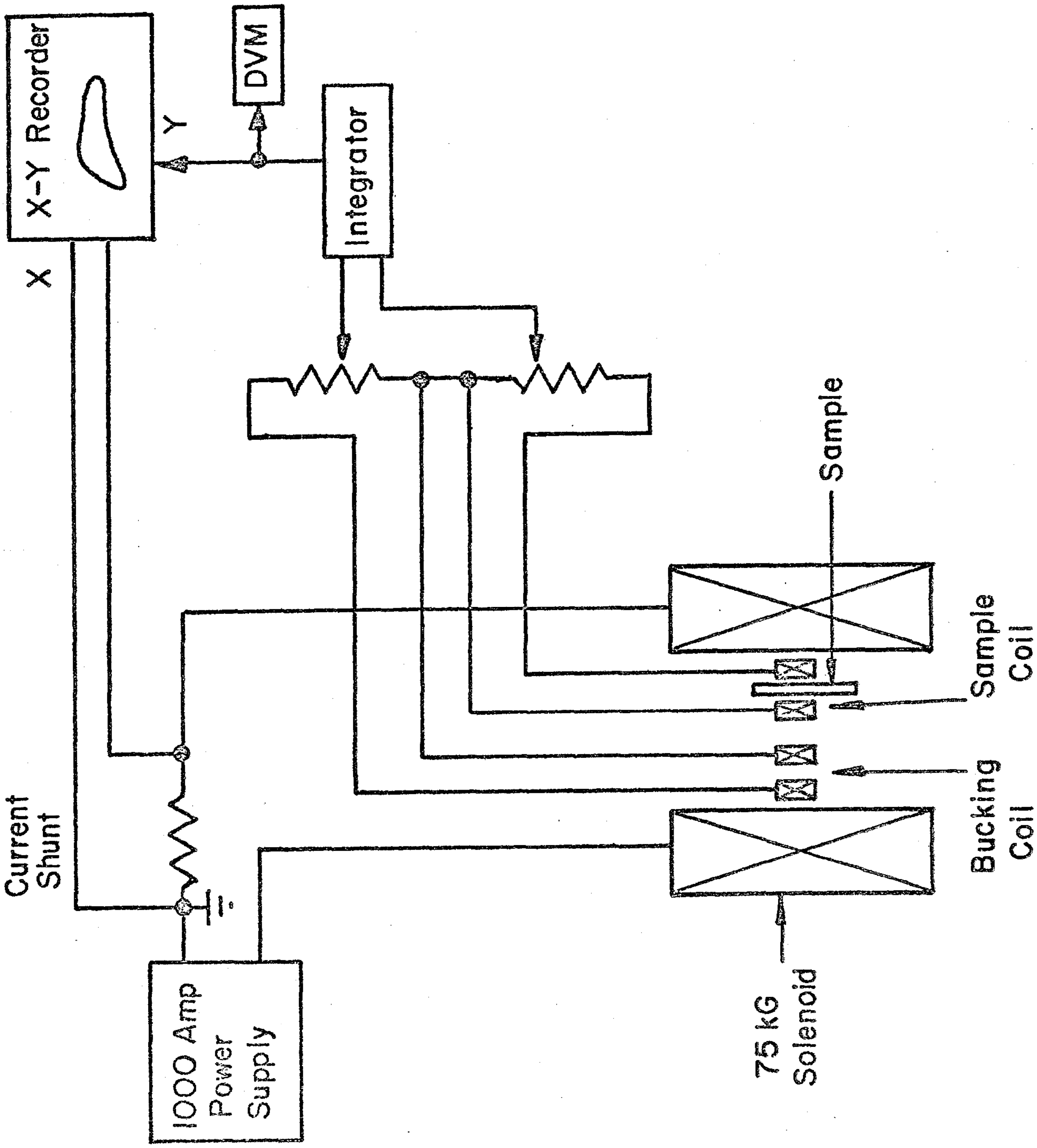

Fig. 3 Block Diagram of Hysteresis Loss Measurement

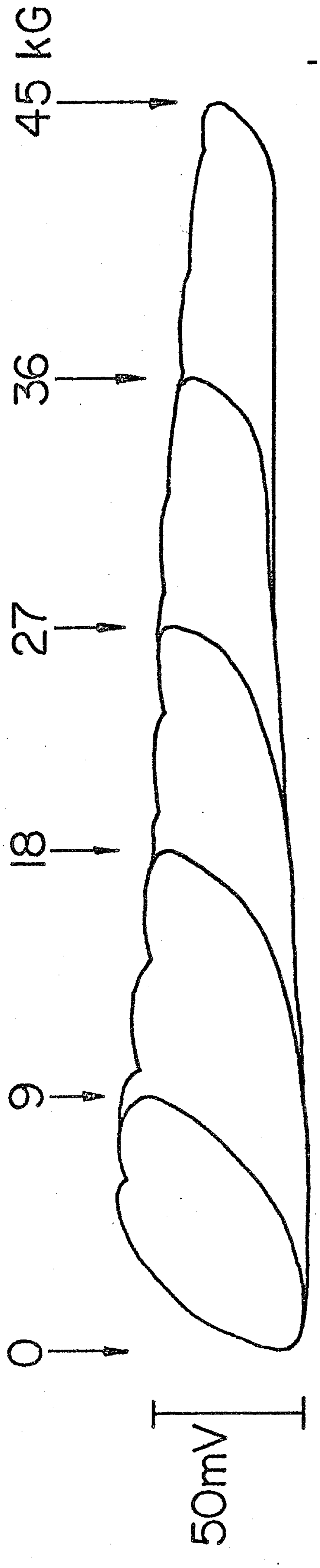

Fig. 4 Hysteresis Loss Loops of MCA Wire
17 strand, 50 × 250 mils

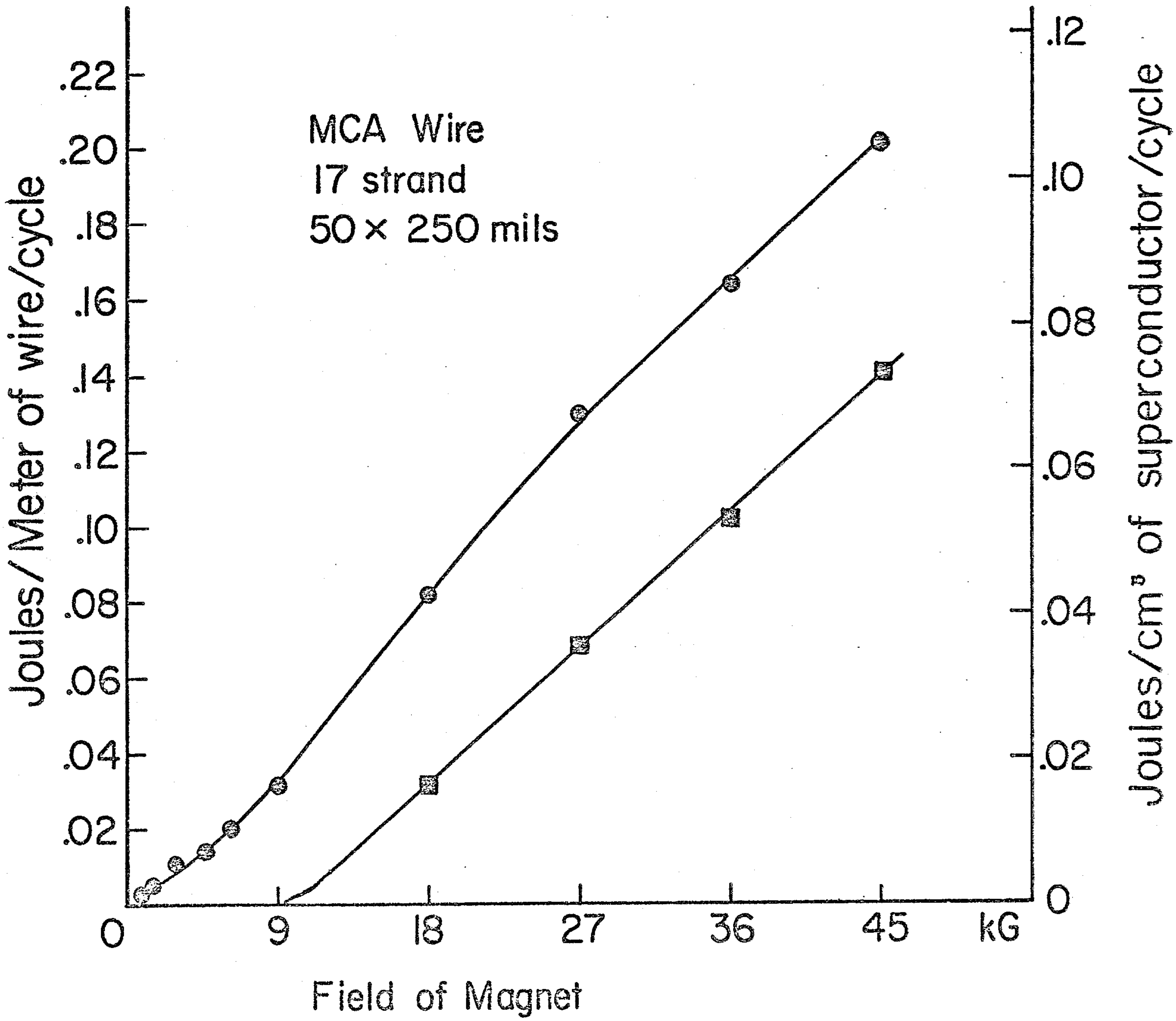

Fig. 5 Hysteresis Loss of MCA Wire
17 strand, 50 × 250 mils

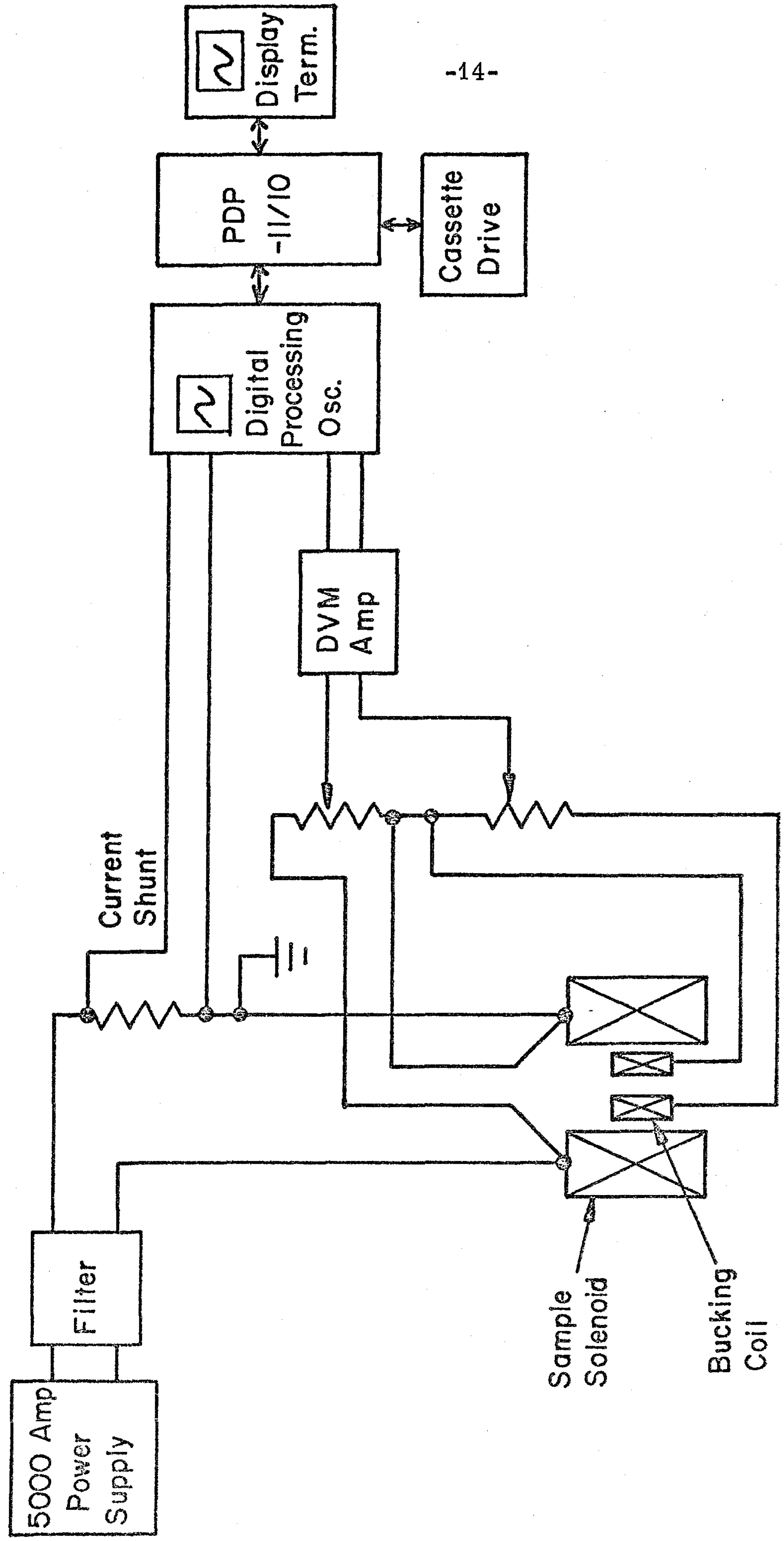

Fig.6 Block Diagram of AC Loss Measurement

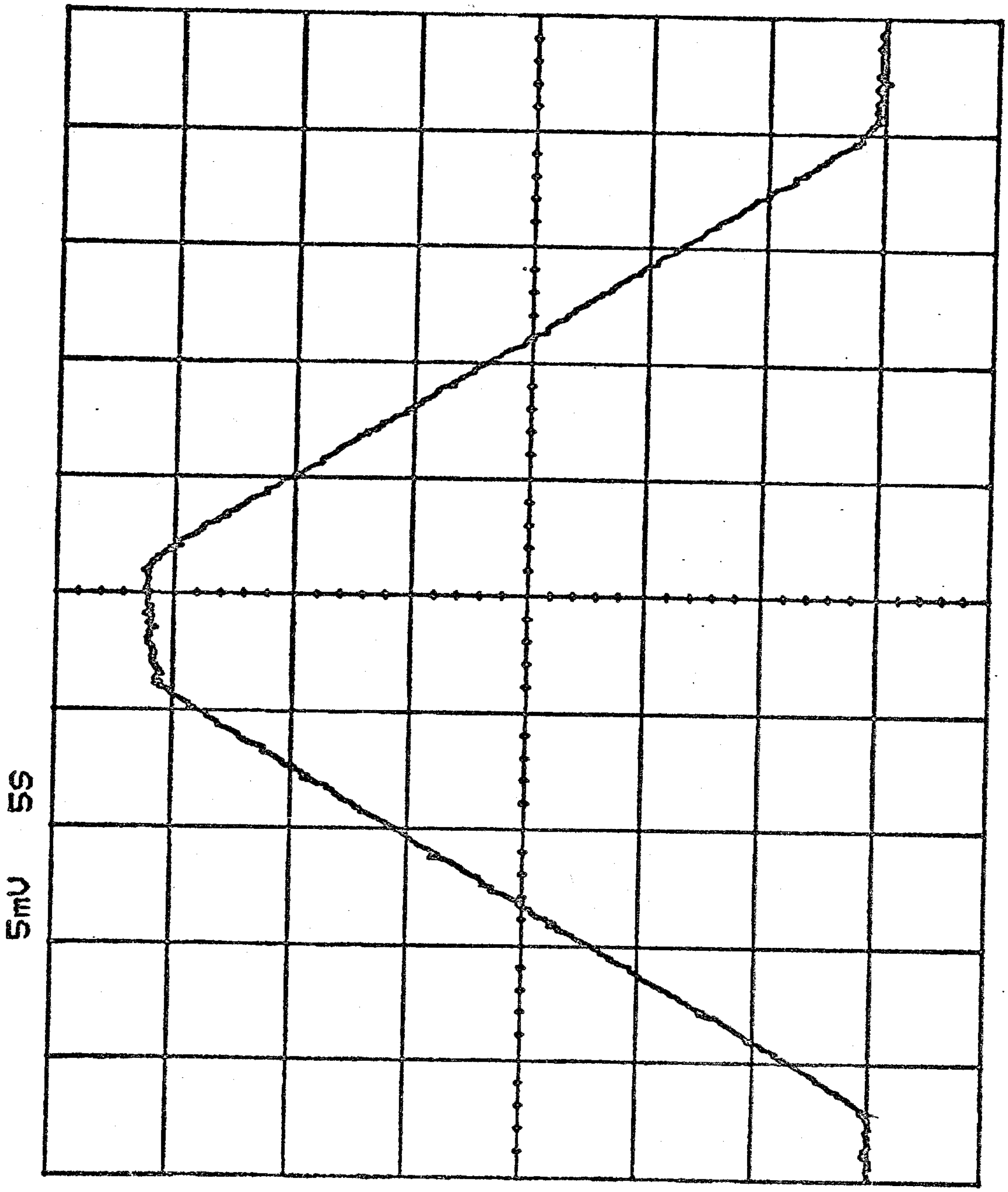

Fig. 7 Current waveform of solenoid
500A/div, 5sec/div

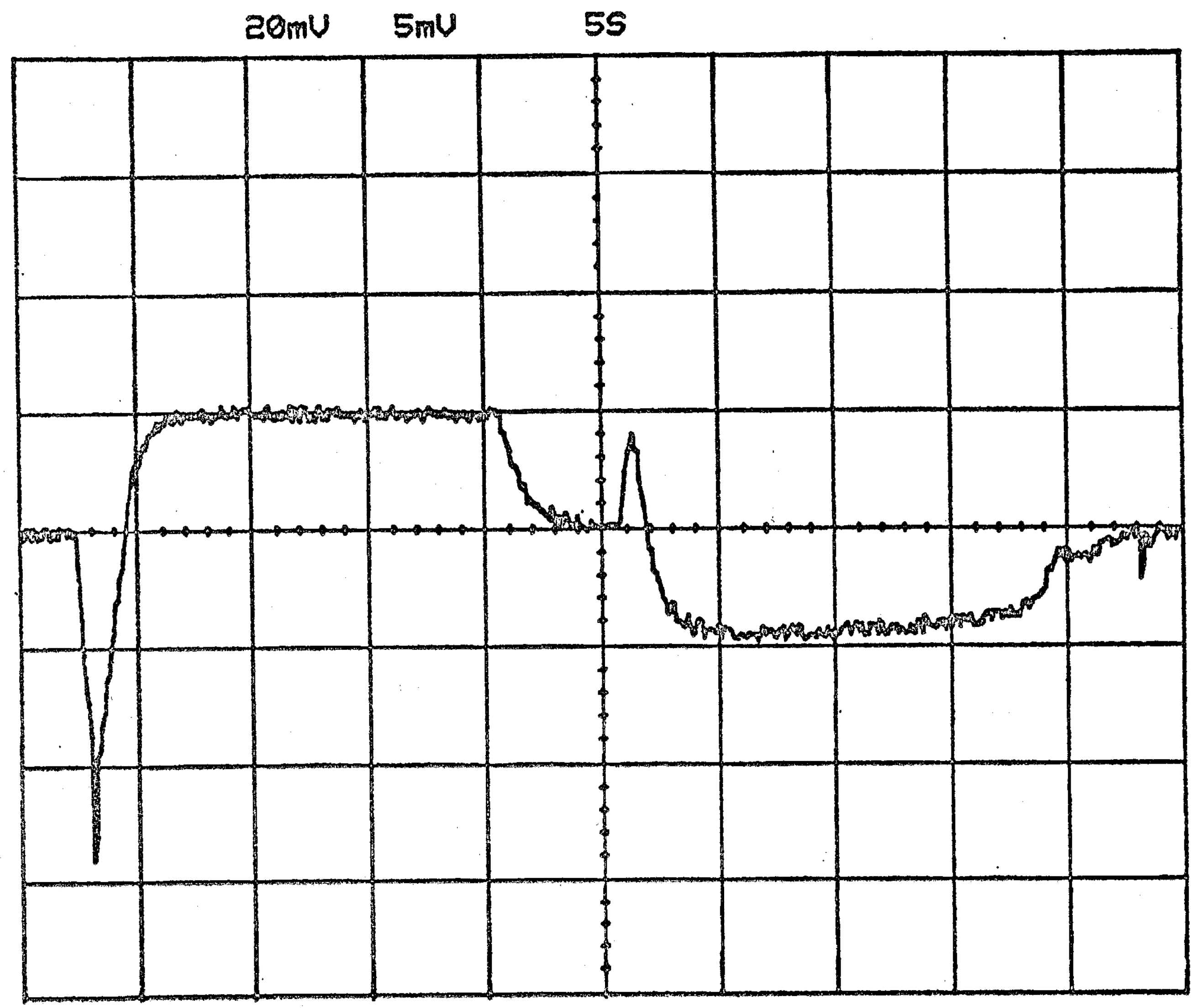

Fig.8 Balanced voltage waveform from solenoid
20mV/div, 5 sec/div

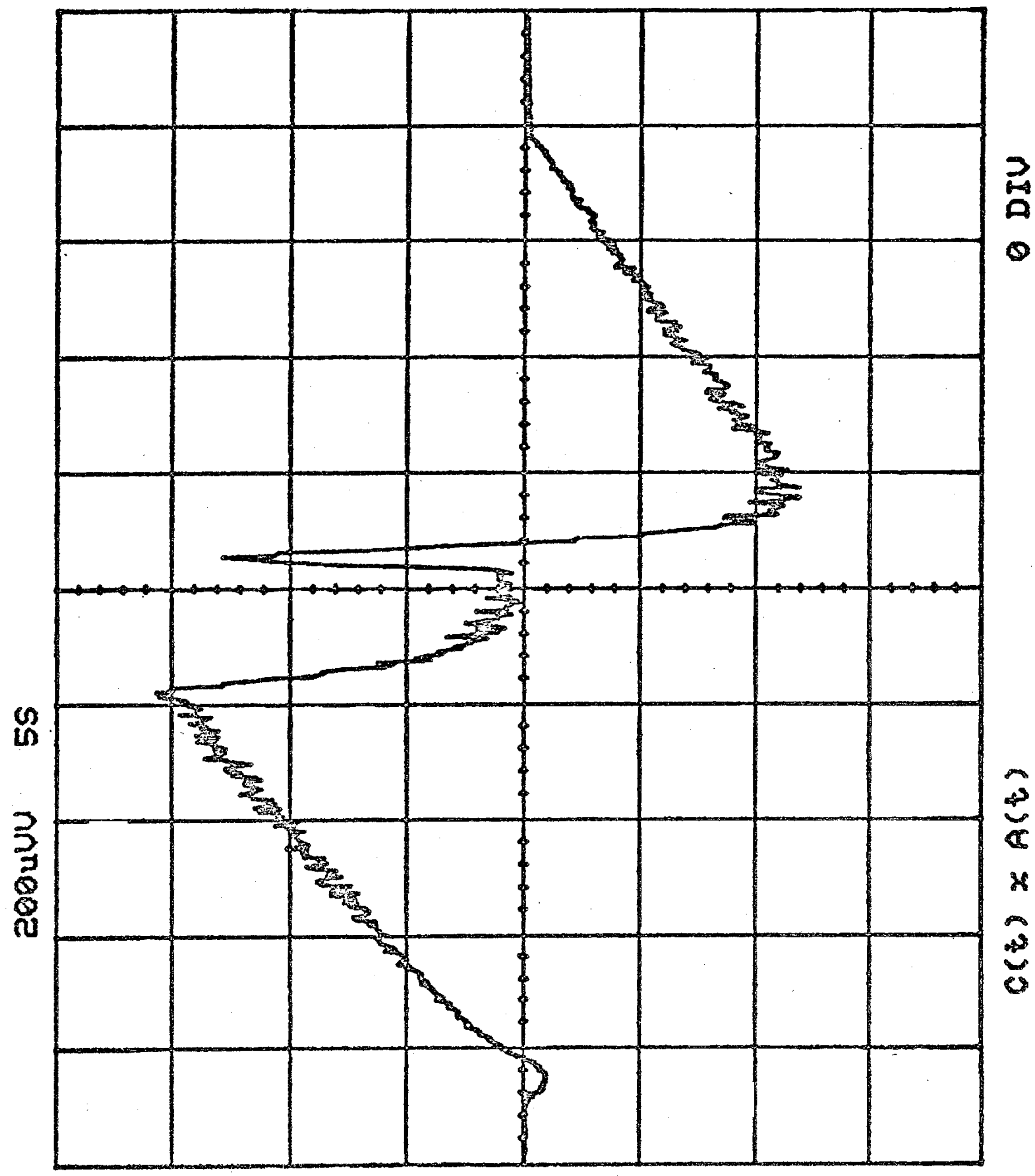

Fig.9 Waveform of Instantaneous Power

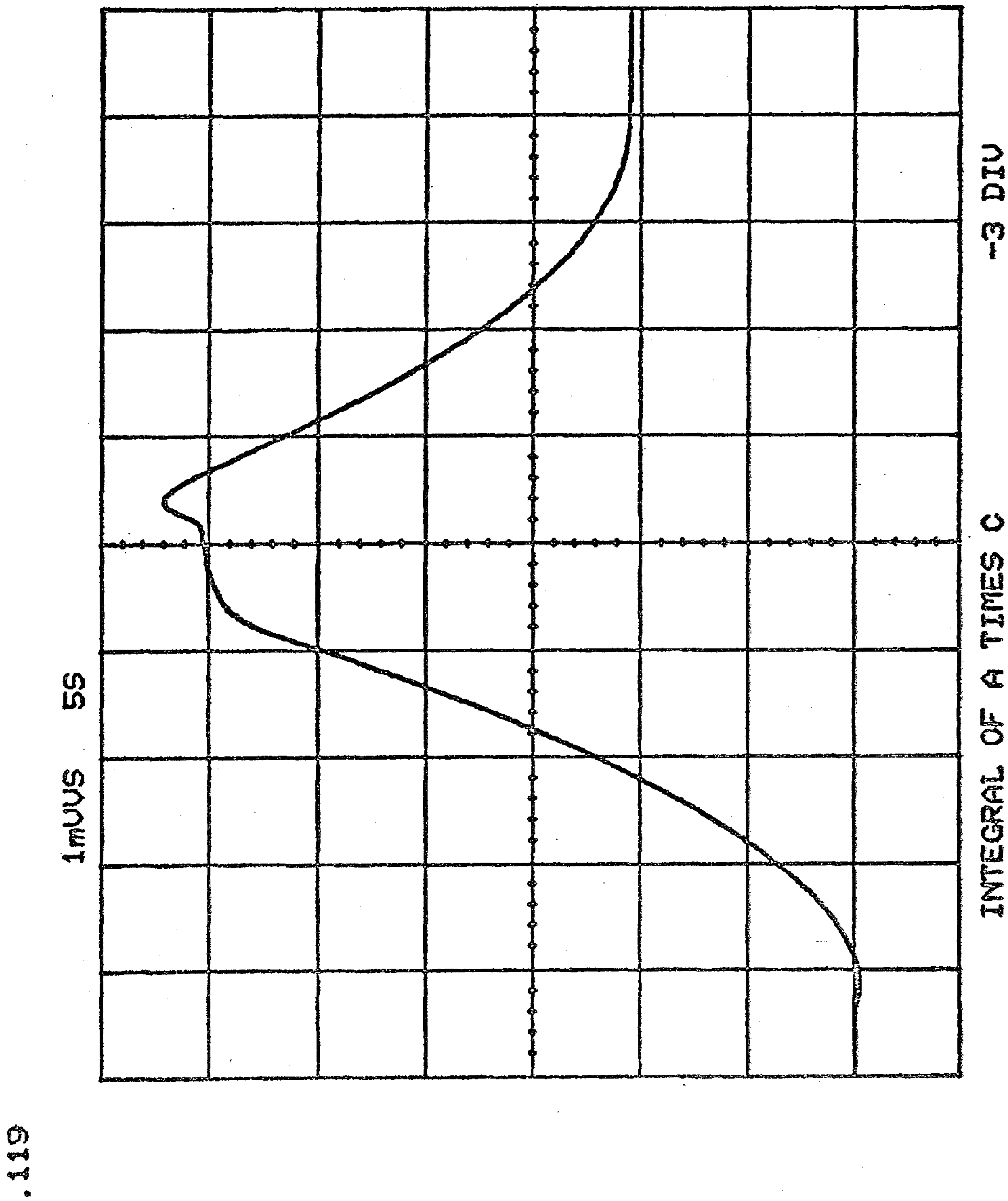

Fig.10 Integration of Instantaneous Power
Last value is AC loss, and printed at left.

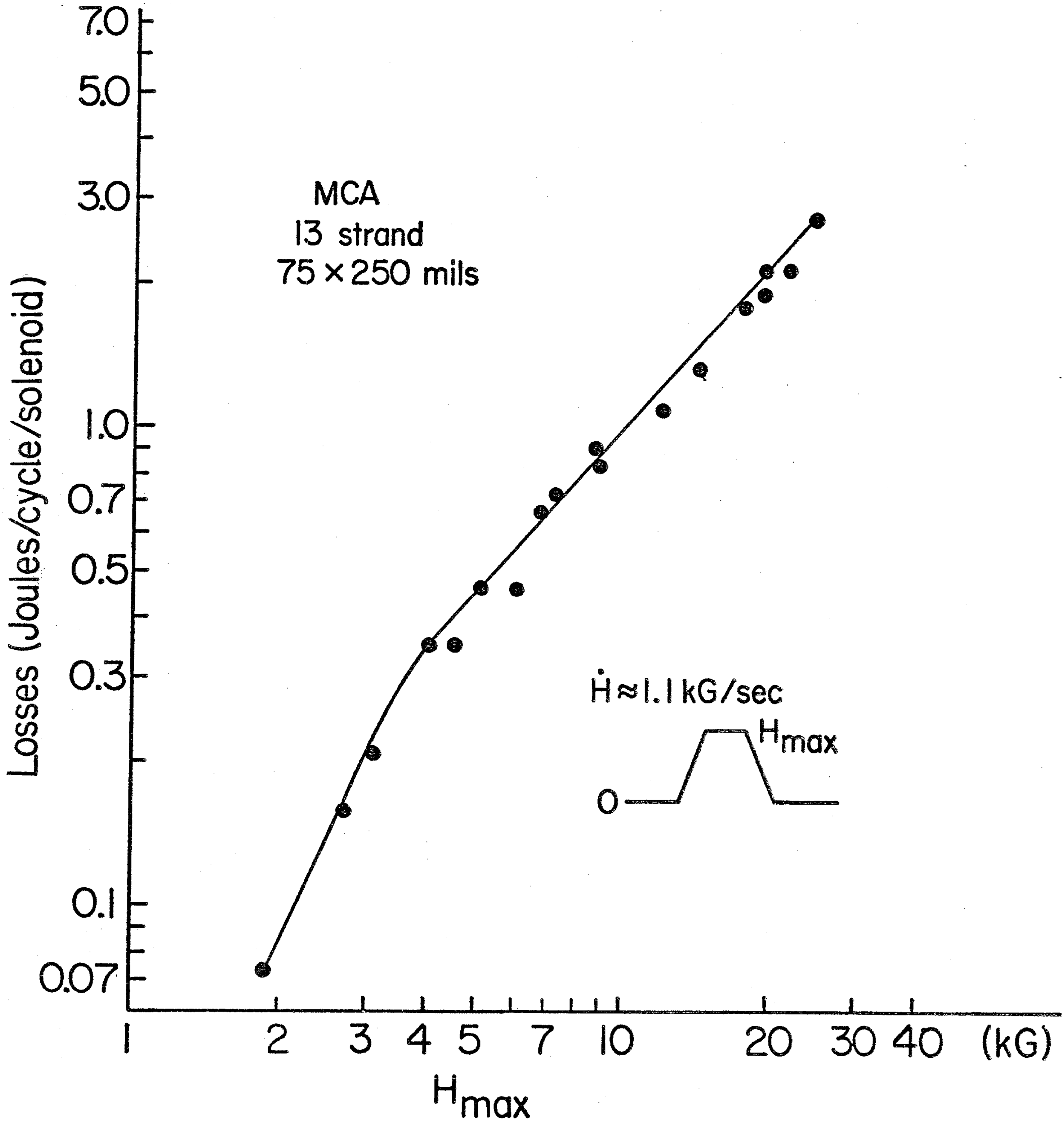

Fig.11 AC loss data of MCA 13 strand wire, amplitude test, measured with $\dot{H} = 1.1$ kG/sec.

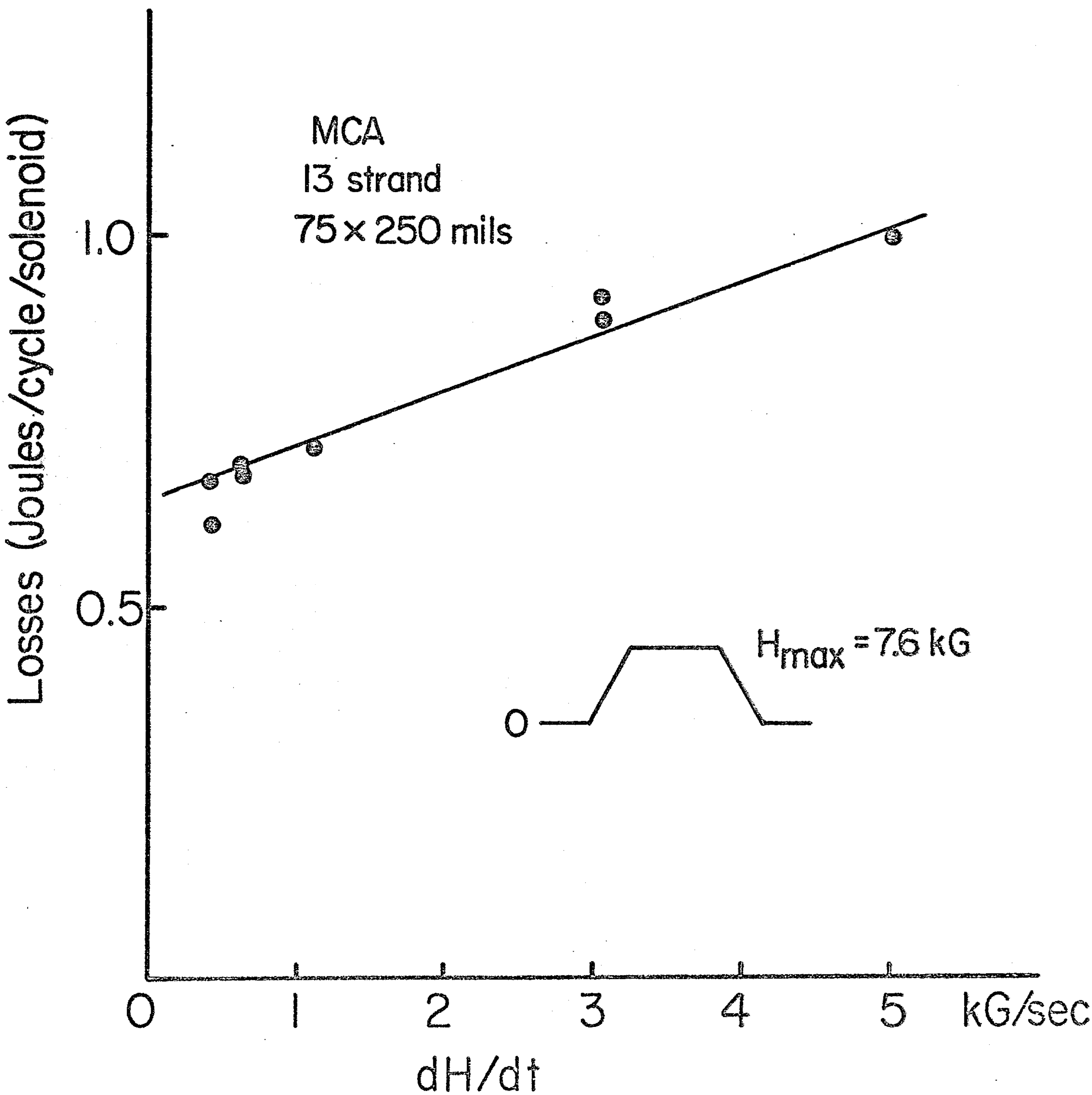

Fig. 12 AC loss data of MCA 13 strand wire, sweep rate test, measured at H_{max} = 7.6 kG